FRAGMENT KINETIC ENERGIES IN SPECTATOR DECAYS

W. TRAUTMANN and T. ODEH for the ALADIN COLLABORATION

Gesellschaft für Schwerionenforschung (GSI)
Planckstr. 1, D-64291 Darmstadt, Germany

Abstract

Kinetic energies of fragments and light particles from the spectator decay in collisions of gold nuclei at relativistic energies have been measured. The memory of the entrance channel is apparent in the kinetic energies of nucleons while evaporation components can be identified in the spectra of nucleons and alpha particles. Beyond that, the mean kinetic energies are typically 40 to 50 MeV, independent of the particle species and the bombarding energy, but not in equilibrium with the chemical or thermal degrees of freedom. It is suggested that the kinetic energies may reflect the Fermi motion within the spectator system prior to its decay.

1 Introduction

The fragmentation of ^{197}Au projectiles at bombarding energies E/A of several hundreds of MeV up to 1 GeV has been extensively studied with the ALADIN spectrometer at SIS [1, 2]. The disintegration of the formed spectator systems into light particles and fragments of intermediate mass was found to exhibit universal features, evident from the observed Z_{bound} scaling of the fragment-charge correlations. The memory of the entrance channel is apparently lost which seems to indicate that excited spectators reach a highly equilibrated state prior to their decay.

The widths of the measured fragment momentum distributions, in the moving frame, are the same in transverse and longitudinal directions. In addition, they are independent of the incident energy [2]. These observations are consistent with equilibration of the kinetic degrees of freedom but also puzzling because the corresponding temperatures are much higher than the breakup temperatures needed for the statistical description of the partition space. The mean kinetic energies in the spectator frame are of the order of 40 to 50 MeV while analyses with statistical multifragmentation models require input temperatures around 6 MeV [3]. The breakup temperatures deduced from measured isotopic yield ratios are also of this magnitude [3, 4].

2 New Data from Experiment S117

In experiment S117 the decay of the target spectator in ^{197}Au + ^{197}Au collisions at E/A = 1000 MeV was studied [3]. High-resolution telescopes were used to measure energy spectra of light charged particles and of intermediate-mass fragments at backward angles. In coincidence, the products of the projectile decay were measured with the time-of-flight wall of the ALADIN spectrometer and Z_{bound} was determined event-by-event. The quantity Z_{bound} is defined as the sum of the atomic numbers Z_i of all projectile fragments with $Z_i \geq 2$ and may serve as a measure for the impact parameter.

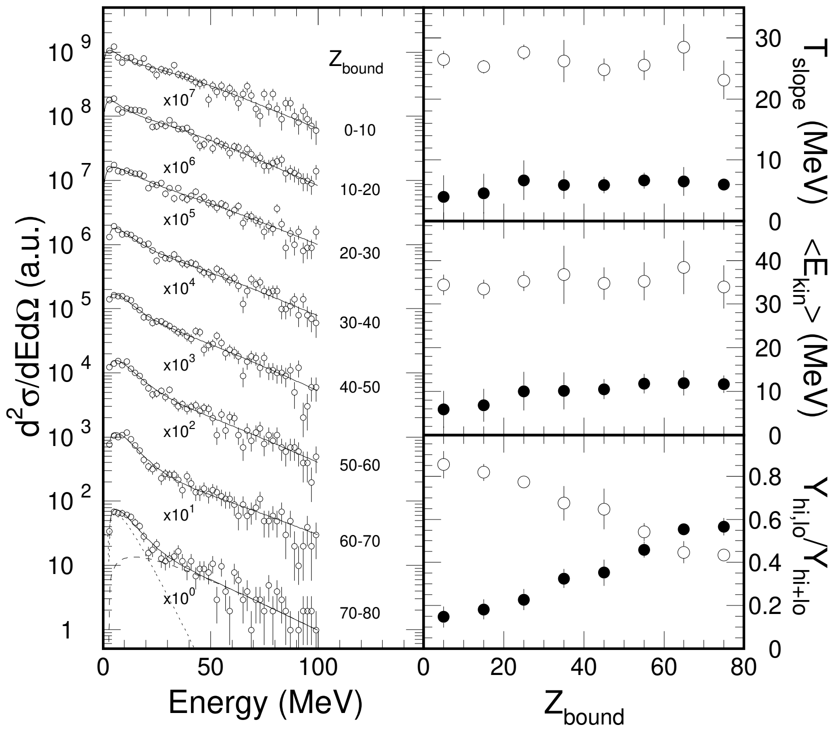

Figure 1: Energy spectra of protons for the indicated intervals of Z_{bound} (left panel) and slope temperatures, mean kinetic energies, and relative yields of the two components with high and low temperatures (right panels). The full lines represent the fit results, the dashed and dotted lines in the bin with largest Z_{bound} show the high and low temperature components individually.

Energy spectra of protons, measured at θ_{lab} = 150° and sorted into eight bins of Z_{bound}, are shown in Fig. 1 (left panel). They exhibit two components with rather different properties. Fits assuming Maxwellian spectral shapes show that the temperature parameters of the two components change very little with Z_{bound} while the relative intensity of the low-temperature component decreases rapidly with decreasing Z_{bound} (Fig. 1, right panels). It has a temperature of $T \approx 5$ MeV and other features expected for evaporation from excited residual nuclei. In particular, its relative intensity is strongly correlated with the intensity of heavier fragmentation products.

Two components have also been identified in the spectra of α particles and in the neutron data measured with LAND [5]. The low-temperature components may be ascribed to evaporation. The high-temperature components of protons and neutrons are consistent with each other if the effect of Coulomb repulsion is taken into account. Neutrons were measured at several bombarding energies, and it was found that their kinetic energies rise with the incident energy. Although equivalent data for proton emission are not yet available we may conclude that these highly energetic nucleon components at spectator rapidity have their origin partly in the initial cascading stages of the collision.

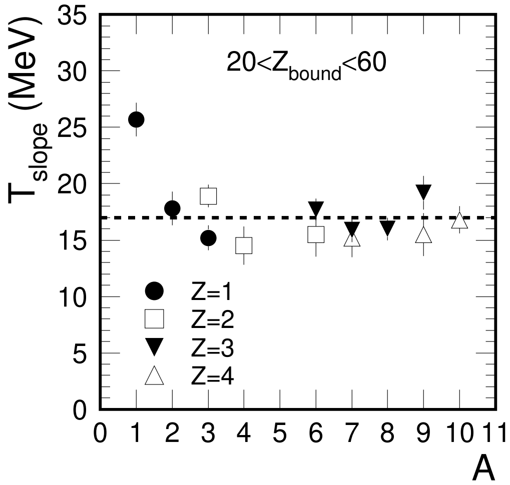

Figure 2: Slope parameters for isotopically resolved charged particles and fragments from the reaction ^{197}Au + ^{197}Au at $E/A = 1000$ MeV, measured at $\Theta_{lab} = 150°$ and integrated over $20 \leq Z_{bound} \leq 60$, as a function of the mass number A. For protons and α particles the value of the high-temperature component is shown.

The high-temperature component of α particles has $T \approx 15$ MeV, a value close to the slope temperatures observed for other species with $A \geq 2$ which have Maxwellian spectral shapes to a good approximation. Their values obtained by integrating over the range $20 \leq Z_{bound} \leq 60$ are shown in Fig. 2. Apart from the protons with $T \approx 26$ MeV, all spectra exhibit temperatures that are scattered closely around a mean value of 17 MeV (dashed line).

The invariance of the slope temperatures with A, at first sight, seems to directly provide additional evidence for equilibration of the kinetic degrees of freedom. On the other hand, Coulomb effects should contribute in proportion to the fragment charge and the small but finite motion of the target spectator should introduce a collective velocity component. In order to identify these effects, we have performed a model study which started from initial spatial configurations generated by randomly placing fragments and light particles in a sphere. The fragment charge distribution was taken from the experiment [2] and the density was chosen as $\rho/\rho_0 = 0.3$ where ρ_0 is the normal nuclear density. The initial values of the fragment kinetic energies were drawn from a thermal distribution of temperature T. Coulomb-trajectory calculations were used to obtain the asymptotic kinetic-energy spectra and their slope temperatures were then determined by fitting.

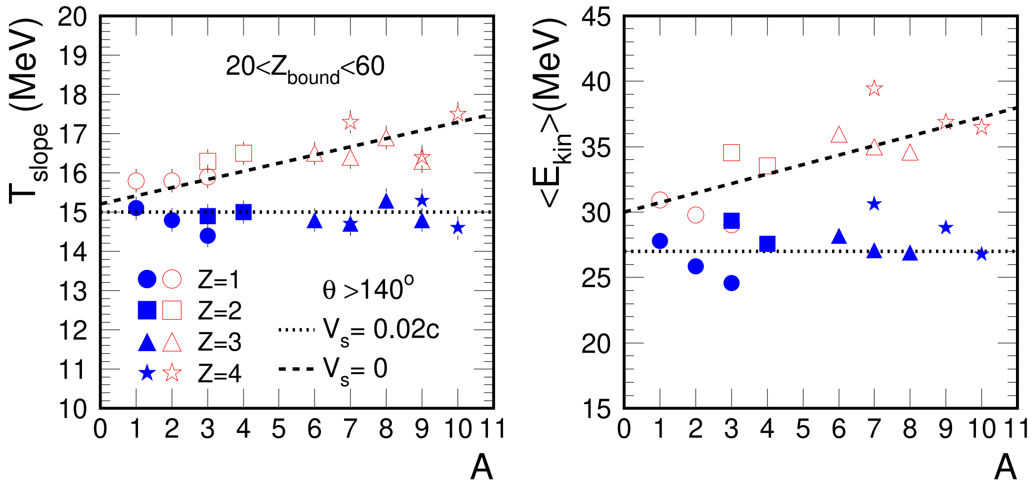

Figure 3: Results of the model study for the decay of a thermalized source with temperature $T = 15$ MeV. The slope temperatures (left panel) and the mean kinetic energies (right panel) for $\Theta_{lab} \geq 140°$ are shown as a function of A and for sources at rest in the laboratory (open symbols, dashed line) and moving with $\beta = 0.02$ in beam direction (full symbols, dotted line).

The results for $T = 15$ MeV, shown in Fig. 3, illustrate the individual contributions of Coulomb repulsion and of the source motion. They demonstrate that, in the present case, both effects cancel each other to a very good approximation. The asymptotic slope parameters have the same value of 15 MeV as the initial temperature. We therefore conclude that the measured slope parameters of $T \approx 17$ MeV (Fig. 2) may indeed be taken as the temperatures in a thermal interpretation of the fragment kinetic energies.

3 Results of Earlier Experiments

The model study also showed that Coulomb repulsion adds considerably to the final kinetic energies (Fig. 3, right panel). This component depends on Z and assumes values between 10 and 20 MeV. Together with the thermal component it adds up to mean kinetic energies in the spectator frame of about 35 to 40 MeV. In the following we will compare this result with earlier measurements and show that they are quite consistent, even though different temperatures or slope parameters may have been derived in different experiments.

First inclusive data, taken several years ago at SATURNE in Saclay, have already demonstrated that the slopes of the fragment spectra harden significantly as the bombarding energy is raised into the relativistic regime [6]. Moving source fits to the measured fragment angular distributions resulted in temperature parameters of the order of 25 MeV. At the same time, rather small values were obtained for the parameter E_C describing the Coulomb potential at the point of emission, e.g. typically $E_C = 10$ MeV for fragments in the reaction ^{12}C + ^{197}Au at $E/A = 600$ MeV. The total mean kinetic energies corresponding to these values are 45 to 50 MeV, their particular division into thermal and Coulomb components may indicate that the Coulomb repulsion is fluctuating to a larger extent than anticipated with the adopted fit function.

In the first experiment with the ALADIN spectrometer at SIS, transverse momentum distributions for fragments above the tracking threshold $Z = 8$ were measured for reactions of ^{197}Au projectiles with targets of C, Al, Cu, and Au at $E/A = 600$ MeV [7]. The obtained width parameters for one transverse component are shown in Fig. 4. The applied correction for the Coulomb repulsion from the target has the effect that the widths become nearly identical in the four cases. Their parabolic dependence on the fragment Z is expected from momentum conservation. A fit according to the prescription given by Goldhaber [8] yields a width parameter $\sigma_0 = 160$ MeV/c which corresponds to a temperature $T = 27$ MeV or mean kinetic energies of about 40 MeV. The temperature parameter is again high because the mutual Coulomb repulsion within the spectator source is not explicitly accounted for.

The rapidity distributions measured with the ALADIN time-of-flight wall for fragments from collisions of ^{197}Au projectiles at energies E/A up to 1 GeV confirm the isotropy of the momentum distributions in the moving frame. Also from these measurement mean kinetic energies of about 40 to 50 MeV were

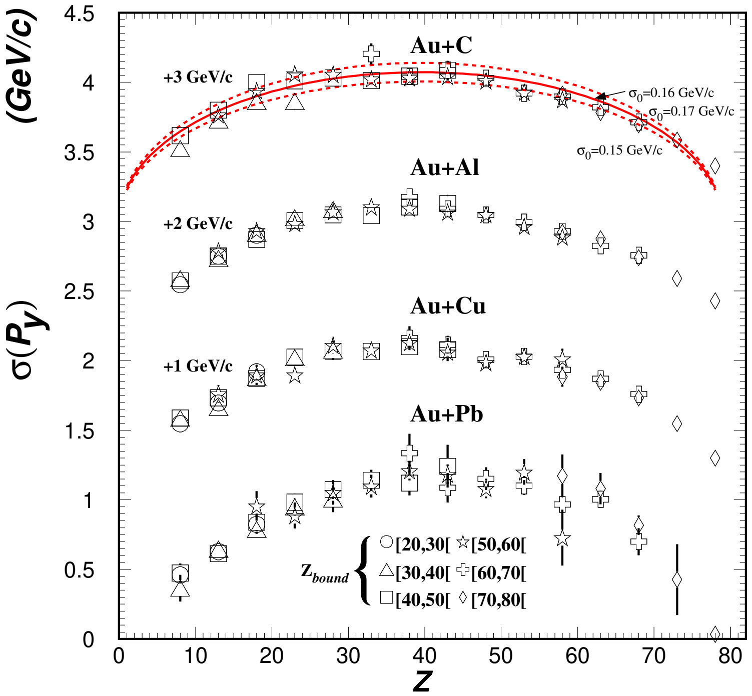

Figure 4: Width of one transverse momentum component as a function of Z for projectile fragments from reactions of ^{197}Au with C, Al, Cu, and Pb targets at a bombarding energy E/A = 600 MeV. A first-order correction for the Coulomb repulsion by the target has been applied. The symbols represent mean values within the indicated intervals of Z_{bound}. The full and dashed lines represent parabolic fits according to ref. [8]. Note the incremented offsets by 1 GeV/c (from ref. [7]).

obtained [2].

As a summary of these measurements and model analyses we may state that the mean kinetic energies of $A \geq 2$ fragments (excluding the low temperature component of ^{4}He) are isotropically distributed, depend neither on the fragment mass nor on the bombarding energy, are between 40 and 50 MeV, and may be described as resulting from the volume breakup of a hot system with temperature $T \approx 17$ MeV.

4 The Role of Fermi Momentum

It was suggested many years ago by Goldhaber that the kinetic energies in fast fragmentation processes may have their origin in the Fermi momenta of the constituent nucleons prior to breakup [8]. He also pointed out that the resulting behavior is indistinguishable from that of the decay of a thermalized system with rather high temperature. We recall here that the momentum parameter that was obtained from fitting the fragmentation data for ^{16}O at E/A = 2.1 GeV is σ_0 = 90 MeV/c. If one starts with the Fermi momentum $p_F \approx$ 265 MeV/c of heavier nuclei the larger value σ_0 = 120 MeV/c is expected which, in the thermal interpretation, corresponds to T = 15 MeV. This is intriguingly close to the measured slope temperature T = 17 MeV but relies on the assumption of a cold breakup at normal nuclear density.

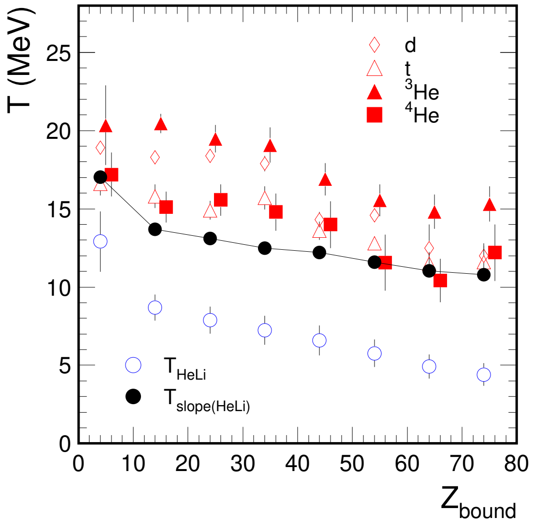

Figure 5: Slope temperatures for light charged particles of mass $2 \leq A \leq 4$ (squares, triangles and diamonds) and the isotope temperature T_{HeLi} (open circles) as a function of Z_{bound}. The full circles are the slope temperatures obtained for the fast breakup of a Fermi gas with finite temperature T_{HeLi} according to ref. [9].

This idea has been extended to the case of expanded fermionic systems at finite temperatures by Bauer [9]. To use the prescription given there the temperature and density of the system prior to its decay have to be specified. If we use the measured breakup temperatures T_{HeLi} [3] and a breakup density ρ/ρ_0 = 0.5 we obtain the slope temperatures shown in Fig. 5. They range between 11 and 17 MeV and come close to those observed. Their rise with decreasing Z_{bound} is a consequence of the changing breakup temperatures.

5 Concluding Remarks

The nearly quantitative agreement of the measured and the estimated slope temperatures (Fig. 5) rests on the chosen breakup density. Lower densities in the range usually assumed for multi-fragment breakups will reduce the Fermi motion and lead to smaller slope temperatures. However, it is not at all clear what density should be chosen. Recent studies using nuclear-molecular dynamics [10] or quantum-molecular dynamics [11] models suggest that fragments may be formed rather early in the collision at densities higher than at the final breakup stage. With the quantum-molecular dynamics which explicitly treats the Fermi motion of the colliding nuclei the measured fragment energies were quite well reproduced [11].

The short time scales of typically 40 fm/c after which the asymptotic fragments can be identified, as suggested by these studies, fit well into a picture of the spectator fragmentation as a rapid process. There seems not to be sufficient time to equilibrate the thermal and kinetic degrees of freedom. Of course, this raises the question why the partition space of the spectator decay is so well described by the statistical fragmentation model in which all degrees of freedom are assumed to be equilibrated [3, 12]. At the same time, it may help to understand why the excitation energies obtained from calorimetric measurements [4] or from dynamical models for the initial reaction phase are larger than those needed for the statistical-decay calculations [1, 2, 5]. The kinetic energies which represent more than half of the total excitation energies contain considerable non-thermal components.

There are other types of reactions leading to multi-fragment decays for which good agreement between measured kinetic-energy distributions and calculations with statistical multifragmentation models has been reported [13, 14]. On the other hand, slope temperatures of 18 to 20 MeV that do not vary with bombarding energy have, e.g., been deduced for non-equilibrium production of intermediate-mass fragments in ^{14}N induced reactions at $E/A \leq 100$ MeV [15]. It will be interesting to follow up on these differences because they may contain valuable clues for a better understanding of the fragment formation processes.

References

[1] P. Kreutz et al., Nucl. Phys. A **556** (1993) 672;

[2] A. Schüttauf et al., Nucl. Phys. A **607** (1996) 457;

[3] Hongfei Xi et al., Z. Phys. A 359 (1997) 397;

[4] J. Pochodzalla et al., Phys. Rev. Lett. **75** (1995) 1040;
[5] C. Groß, PhD thesis, Universität Frankfurt (1998);
[6] U. Milkau et al., Phys. Rev. **C44** (1991) R1242;
[7] V. Lindenstruth, PhD thesis, Universität Frankfurt (1993);
[8] A.S. Goldhaber, Phys. Lett. **53B** (1974) 306;
[9] W. Bauer, Phys. Rev. **C51** (1995) 803;
[10] H.W. Barz et al., Phys. Lett. B **382** (1996) 343;
[11] P.B. Gossiaux et al., Nucl. Phys. A **619** (1997) 379;
[12] A.S. Botvina et al., Nucl. Phys. A **584** (1995) 737;
[13] M. D'Agostino et al., Phys. Lett. B **371** (1996) 175;
[14] S.P. Avdeyev et al., Eur. Phys. J. A **3** (1998) 75;
[15] J.L. Wile et al., Phys. Rev. **C45** (1992) 2300.